

The Imprint of Cosmic Reionization on Galaxy Clustering

J. Stuart B. Wyithe¹ & Abraham Loeb²

¹ *School of Physics, University of Melbourne, Parkville, Victoria, Australia*

² *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138*

Email: swyithe@physics.unimelb.edu.au, aloeb@cfa.harvard.edu

5 February 2008

ABSTRACT

We consider the effect of reionization on the clustering properties of galaxy samples at intermediate redshifts ($z \sim 0.3\text{--}5.5$). Current models for the reionization of intergalactic hydrogen predict that overdense regions will be reionized early, thus delaying the build up of stellar mass in the progenitors of massive lower-redshift galaxies. As a result, the stellar populations observed in intermediate redshift galaxies are somewhat younger and hence brighter in overdense regions of the Universe. Galaxy surveys would therefore be sensitive to galaxies with a somewhat lower dark matter mass in overdense regions. The corresponding increase in the observed number density of galaxies can be parameterized as a galaxy bias due to reionization. We model this process using merger trees combined with a stellar synthesis code. Our model demonstrates that reionization has a significant effect on the clustering properties of galaxy samples that are selected based on their star-formation properties. The bias correction in Lyman-break galaxies (including those in proposed baryonic oscillation surveys at $z < 1$) is at the level of 10–20% for a halo mass of $10^{12} M_{\odot}$, leading to corrections factors of 1.5–2 in the halo mass inferred from measurements of clustering length. The reionization of helium could also lead to a sharp increase in the amplitude of the galaxy correlation function at $z \sim 3$. We find that the reionization bias is approximately independent of scale and halo mass. However since the traditional galaxy bias is mass dependent, the reionization bias becomes relatively more important for lower mass systems. The correction to the bias due to reionization is very small in surveys of luminous red galaxies at $z < 1$.

Key words: cosmology: diffuse radiation, large scale structure, theory – galaxies: high redshift, intergalactic medium

1 INTRODUCTION

The clustering of galaxies is often used to study the power-spectrum of the underlying mass distribution (e.g. Tegmark et al. 2006). Since the data does not reflect the clustering of mass but rather the clustering of galaxies, a correction factor termed *the galaxy bias* must be applied to its analysis. This bias factor is a mass (and possibly scale) dependent property of the galaxy population. Alternatively, assuming that the mass power-spectrum is known, the masses of the galaxies can be inferred from their bias by comparing the expected clustering of mass with the observed galaxy clustering. In either case, if one is trying to determine galaxy mass using clustering or one is trying to determine the underlying properties of the mass power-spectra from observations of galaxy clustering, a theoretical understanding of galaxy bias is required. As a first estimate, the bias can be calculated from linear theory (Mo & White 1996; Sheth, Mo

& Tormen 2001). In addition, through comparison with N-body simulations, various corrections to the bias have also been calculated (see Eisenstein et al. 2005 for a summary) to allow more accurate comparisons with improving data. These contributions to the bias are physical in the sense that they are due only to the properties of the dark matter, and so they can be computed (albeit via simulation) from first principles given an input mass power-spectrum.

Recently it has been suggested that an inhomogeneous reionization can lead to a modification of the observed clustering of galaxies. Babich & Loeb (2006) calculated the modulation of the number density of the lowest-mass galaxies that result from reionization induced variation in the thermal history among different regions of the IGM. Although they have found that the expected effect on the galaxy power-spectrum is much larger than the difference between competing models of inflation, their analysis did not extend to high mass galaxies to which future surveys will be sen-

sitive. Pritchard, Furlanetto & Kamionkowski (2007) considered lower redshifts and more massive galaxies, but used an ad-hoc ansatz that the overdensity of galaxies is proportional to the underlying radiation field and concluded that reionization would leave a redshift dependent imprint on the galaxy power-spectrum at low redshifts that might interfere with measurements of the baryonic acoustic peak. These papers did not attempt to compute the coupling between the mass-to-light ratio of massive galaxies and the large scale environment. However galaxy surveys produce clustering statistics for either flux limited surveys, or for volume limited surveys in a fixed luminosity range. Computation of the effect of reionization on the mass-to-light ratio of massive galaxies is therefore critical for comparison with any real survey.

The aim of this paper is to estimate the *astrophysical* contribution to the galaxy bias due to the reionization of the intergalactic medium (IGM). This contribution is model dependent, requiring knowledge of the baryonic physics in addition to gravity. The reionization of the IGM is sensitive to the local large-scale overdensity. In regions that are overdense, galaxies are over-abundant for two reasons: first because there is more material per unit volume to make galaxies, and second because small-scale fluctuations need to be of lower amplitude to form a galaxy when embedded in a larger-scale overdensity. The first effect will result in a larger density of ionizing sources. However this larger density will be compensated by the increased density of gas to be ionized. In addition, the recombination rate is increased in overdense regions, but this effect is counteracted by the bias of galaxies in these regions. The process of reionization also contains several layers of feedback. Radiative feedback heats the IGM and results in the suppression of low-mass galaxy formation (Efstathiou, 1992; Thoul & Weinberg 1996; Quinn et al. 1996; Dijkstra et al. 2004). This delays the completion of reionization by lowering the local star formation rate, but here again the effect is counteracted in overdense regions by the biased formation of massive galaxies. The radiation feedback may therefore be more important in low-density regions where small galaxies contribute more significantly to the ionizing flux. Wyithe & Loeb (2007) have modeled the density dependent reionization process using a semi-analytic model that incorporates the features described above, and so captures the important physical processes. This model demonstrated that galaxy bias leads to enhanced reionization in overdense regions, so that overdense regions are reionized first.

We show that this early reionization leads to an additional bias in the observed clustering at later epochs in addition to that associated with enhanced structure formation. We find that the correction to the linear bias due to reionization could be significantly larger than other corrections that have been previously considered. Moreover, we show that the bias correction is larger than the uncertainties in current surveys over a wide range of redshifts between $1 \lesssim z \lesssim 5$.

The outline of the paper is as follows. In § 2 and § 3 we describe the effect of reionization on galaxy formation, and summarize galaxy bias. We then outline the reasons why we would expect reionization to yield an additional galaxy bias in § 4, before presenting a model to allow quantitative predictions of the effect (§ 5). We then apply our model to

surveys for Ly-break galaxies (§ 6) and surveys to measure baryonic acoustic oscillations (§ 7). We then discuss some outstanding issues in § 8 before summarizing our conclusions in § 9. Throughout the paper we adopt the latest set of cosmological parameters determined by *WMAP* (Spergel et al. 2006) for a flat Λ CDM universe.

2 REIONIZATION AND OBSERVED GALAXY FORMATION

The dominant effect of reionization on galaxy formation is believed to involve radiative feedback which heats the IGM following the reionization of a region, and thus results in the suppression of low-mass galaxy formation (Efstathiou, 1992; Thoul & Weinberg 1996; Quinn et al. 1996; Dijkstra et al. 2004). Standard models of the reionization process assume a minimum threshold mass for galaxy halos in which cooling and star formation occur (M_{cool}) within neutral regions of the IGM. In ionized regions the minimum halo mass is limited by the Jeans mass (Barkana & Loeb 2001) in an ionized IGM (M_{ion}). We assume M_{cool} to correspond to a virial temperature of 10^4K , representing the hydrogen cooling threshold, and M_{ion} to correspond to a virial temperature of 10^5K , representing the mass below which infall is suppressed from an IGM in which hydrogen has been ionized (Dijkstra et al. 2004).

Observations suggest that hydrogen was reionized by stars prior to $z \sim 6$ (e.g. White et al. 2003; Fan et al. 2006). However models of HeIII reionization suggest that it was the rise of quasars (with harder spectra) that resulted in the overlap of HeIII regions at a redshift of $z \sim 3.5$ (e.g. Wyithe & Loeb 2003; Sokasian et al. 2003). This prediction is consistent with observations that show transmission just blueward of the helium Ly α line at $z \sim 3$ (Jacobsen et al 1994; Tytler 1995; Davidsen et al. 1996; Hogan et al. 1997; Reimers et al. 1997; Heap et al. 2000; Kriss et al. 2001; Smette et al. 2002). In addition, the double reionization of helium results in the temperature of the IGM being approximately doubled (Schaye et al. 2000; Theuns et al. 2002, 2002b). Thus we assume the IGM temperature to change from $T_{\text{IGM}} \sim 10^4\text{K}$ to $T_{\text{IGM}} \sim 2 \times 10^4\text{K}$ between $z \sim 4$ and $z \sim 3$. Calculation of the accretion of baryons from an adiabatically expanding IGM into a dark matter potential well show that the minimum virial temperature for significant accretion is proportional to the temperature of the IGM (Barkana & Loeb 2001). Thus, when helium is reionized at $z \sim 3.5$, the value of T_{min} is doubled from T_{ion} to $2T_{\text{ion}}$. When considering Helium reionization we assume a sudden heating ($\Delta z \lesssim 0.1$). However we note that the period of heating could be more prolonged.

3 GALAXY BIAS

Strong clustering of massive galaxies in overdense regions implies that these sources trace the higher density regions of IGM. The clustering of galaxies is driven by two effects. The first effect is the underlying clustering of the density field. This clustering may be expressed via the mass correlation function between regions of mass M_1 and M_2 , separated by a comoving distance R is (see Scannapieco & Barkana 2002

and references therein)

$$\xi_m(M_1, M_2, R) = \frac{1}{2\pi^2} \int dk k^2 P(k) \times \frac{\sin(kR)}{kR} W(kR_1) W(kR_2), \quad (1)$$

where

$$R_{1,2} = \left(\frac{3M_{1,2}}{4\pi\rho_m} \right)^{1/3}, \quad (2)$$

W is the window function (top-hat in real space), $P(k)$ the power spectrum and ρ_m is the cosmic mass density. The dark-matter halo correlation function for halos of mass M is obtained from the product of the mass correlation function $\xi_m(M, M, R)$ and the square of the ratio between the variances of the halo and mass distributions. This ratio, b , is defined as the halo bias. This bias has been discussed extensively in the literature, (e.g. Mo & White 1996; Sheth, Mo & Tormen 2001). However we briefly describe a likelihood based interpretation which allows the effects of reionization to be included in a natural way.

To see the origin of bias due to enhanced galaxy formation in overdense regions, consider the likelihood (which is proportional to the local number density of galaxies) of observing a galaxy at a random location. Given a large scale overdensity δ of comoving radius R , the likelihood of observing a galaxy may be estimated from the Sheth-Tormen (2002) mass function as

$$\mathcal{L}_g(\delta) = \frac{(1+\delta)\nu(1+\nu^{-2p})e^{-a\nu^2/2}}{\bar{\nu}(1+\bar{\nu}^{-2p})e^{-a\bar{\nu}^2/2}}, \quad (3)$$

where $\nu = (\delta_c - \delta)/[\sigma(R)]$, $\bar{\nu} = \delta_c/[\sigma(R)]$ and $\delta_c \approx 1.69$ is the critical linear overdensity for collapse to a bound object. Here $\sigma(R)$ is the variance of the density field smoothed with a top-hat window on a scale R at redshift z , and $a = 0.707$ and $p = 0.3$ are constants. Note that here as elsewhere in this paper we work with over-densities and variances computed at the redshift of interest (i.e. not extrapolated to $z = 0$). Equation (3) is simply the ratio of the number density of halos in a region of overdensity δ to the number density of halos in the background universe. This ratio has been used to derive the bias for small values of δ (Mo & White 1996; Sheth, Mo & Tormen 2001). For example, in the Press-Schechter (1974) formalism we write

$$\begin{aligned} \mathcal{L}_g(\delta) &= (1+\delta) \left[\frac{dn}{dM}(\bar{\nu}) + \frac{d^2n}{dM d\nu}(\nu) \frac{d\nu}{d\delta} \right] \left[\frac{dn}{dM}(\bar{\nu}) \right]^{-1} \\ &\sim 1 + \delta \left(1 + \frac{\nu^2 - 1}{\sigma(M)\nu} \right) \equiv 1 + \delta b_g, \end{aligned} \quad (4)$$

where $(dn/dM)(\bar{\nu})$ and $(dn/dM)(\nu)$ are the average and perturbed mass functions, and b_g is defined as the bias factor.

The observed overdensity of galaxies is $\delta_{\text{gal}} = 4/3 \times b_g(M, z)\delta$, where $b_g(M, z)$ is the galaxy bias, and the prefactor of $4/3$ arises from a spherical average over the infall peculiar velocities (Kaiser 1987). The value of bias b_g for a halo mass M may be better approximated using the Press-Schechter formalism (Mo & White 1996), modified to include

non-spherical collapse (Sheth, Mo & Tormen 2001)

$$b_g(M, z) = 1 + \frac{1}{\delta_c} \left[\nu'^2 + b\nu'^{2(1-c)} - \frac{\nu'^{2c}/\sqrt{a}}{\nu'^{2c} + b(1-c)(1-c/2)} \right], \quad (5)$$

where $\nu \equiv \delta_c^2/\sigma^2(M)$, $\nu' \equiv \sqrt{a}\nu$, $a = 0.707$, $b = 0.5$ and $c = 0.6$. Here $\sigma(M)$ is the variance of the density field smoothed on a mass scale M at redshift z . This expression yields an accurate approximation to the halo bias determined from N-body simulations (Sheth, Mo & Tormen 2001). Note that in linear theory the bias (equations 4 and 5) is a function of halo mass, but not of overdensity or scale.

4 REIONIZATION INDUCED GALAXY BIAS IN OBSERVED GALAXY SAMPLES

We next introduce an additional galaxy bias due to reionization. In addition to color selection criteria, clustering surveys typically consider galaxies that are either selected to be above a minimum flux threshold (e.g. Adelberger et al. 2005) or to lie in a particular absolute magnitude range (e.g. Eisenstein et al. 2005). Suppose that reionization caused an overdensity dependent change in the flux per unit halo mass by a factor μ . In either of the selection scenarios mentioned above, this effect will result in the host halos of survey galaxies being smaller in that region by an average factor μ . Following the previous formalism, we find the likelihood for observing a galaxy which is subject to a decrease in mass-to-light ratio of μ in a region of overdensity δ ,

$$\begin{aligned} \mathcal{L}_{\text{reion}}(\delta) &= \left[(1+\delta) \frac{dn}{dM}(\nu_\mu) \right] \left[(1+\delta) \frac{dn}{dM}(\nu) \right]^{-1} \\ &\equiv 1 + \delta b_{\text{reion}}(\delta), \end{aligned} \quad (6)$$

where $(dn/dM)(\nu_\mu)$ is the perturbed mass function evaluated at M/μ , and $b_{\text{reion}}(\delta)$ is defined to be the bias factor due to reionization and which could be a function of δ . Note that since surveys are magnitude limited or measured in logarithmic bins of luminosity, there is no factor of μ^{-1} as would be required when discussing the number-counts per unit luminosity¹.

We may then write an expression for the likelihood of observing a galaxy that includes both the bias due to enhanced formation in overdense regions, and a possible effect of reionization

$$\begin{aligned} \mathcal{L}(\delta) &= \mathcal{L}_g(\delta) \times \mathcal{L}_{\text{reion}}(\delta) \\ &= (1 + b_g\delta) \times (1 + b_{\text{reion}}\delta) \\ &\sim 1 + [b_g + b_{\text{reion}}(\delta)]\delta. \end{aligned} \quad (7)$$

In the second equality we have parameterized the effect of variance in the reionization redshift is an additive contribution to the galaxy bias, and have then noted (in the third equality) that we are working in a regime where $b \times \delta \ll 1$. In the next section we will develop a model that will allow us to estimate the magnitude of this effect.

¹ There is also no factor of μ^{-1} to account for depletion as would be appropriate if the enhancement in flux were due to gravitational lensing.

5 PATCHY REIONIZATION AND GALAXY BIAS

In this section we describe a model for the effect of reionization on galaxy bias, and show that reionization increases the bias in the observed overdensity of galaxies relative to the underlying density field. In later sections we will use this model to make qualitative predictions for the impact of reionization on observed clustering in a range of galaxy samples. Our intention is not to produce a detailed model in order to make quantitative predictions or comparisons with the data. Such a model would require detailed numerical simulations, and would in any case require a number of uncertain astrophysical assumptions. However our model is adequate for the purposes of assessing the importance of reionization in clustering measurements, and for making qualitative predictions about its dependence on quantities such as survey redshift and luminosity.

5.1 Reionization redshift and large scale overdensity

Large-scale inhomogeneity in the cosmic density field leads to structure-formation that is enhanced in overdense regions and delayed in under-dense regions. Thus, overlap of ionized regions and hence heating of the IGM would have occurred at different times in different regions due to the cosmic scatter in the process of structure formation within finite spatial volumes (Barkana & Loeb 2004). The reionization of hydrogen would have been completed within a region of comoving radius R when the fraction of mass incorporated into collapsed objects in that region attained a certain critical value, corresponding to a threshold number of ionizing photons emitted per baryon. The ionization state of a region is governed by the enclosed ionizing luminosity, by its overdensity, and by dense pockets of neutral gas that are self-shielding to ionizing radiation. There is an offset (Barkana & Loeb 2004) δz between the redshift when a region of mean overdensity δ achieves this critical collapsed fraction, and the redshift \bar{z} when the universe achieves the same collapsed fraction on average. This offset may be computed (Barkana & Loeb 2004) from the expression for the collapsed fraction (Bond et al. 1991) F_{col} within a region of overdensity δ on a comoving scale R ,

$$F_{\text{col}}(M_{\text{min}}) = \text{erfc} \left[\frac{\delta_c - \delta}{\sqrt{2[\sigma_{R_{\text{min}}}^2 - \sigma_R^2]}} \right], \quad (8)$$

yielding

$$\frac{\delta z}{(1 + \bar{z})} = \frac{\delta}{\delta_c} - \left[1 - \sqrt{1 - \frac{\sigma_R^2}{\sigma_{R_{\text{min}}}^2}} \right], \quad (9)$$

where σ_R and $\sigma_{R_{\text{min}}}$ are the variances in the power-spectrum at z on comoving scales corresponding to the region of interest and to the minimum galaxy mass M_{min} , respectively. On large scales equation (9) reduces to

$$\delta z \approx (1 + z) \frac{\delta}{\delta_c} \quad (10)$$

The offset in the ionization redshift of a region depends on its linear overdensity, δ . As a result, the distribution of offsets, and therefore the scatter in the reionization redshift

may be obtained directly from the power spectrum of primordial inhomogeneities (Wyithe & Loeb 2004). As can be seen from equation (10), larger regions have a smaller scatter due to their smaller cosmic variance. Note that equation (10) is independent of the critical value of the collapsed fraction required for reionization. We also note that since at high redshift the variance of the linear density field increases approximately in proportion to $(1 + z)^{-1}$, the typical delay in *redshift* is almost independent of cosmic time (in addition to not being a function of collapsed fraction).

Following the reionization of hydrogen, doubly ionized helium remained in the pre-overlap phase. At this time, the mean-free-path of HeIII ionizing photons was therefore limited to be smaller than the size of the HeIII regions. As is the case for hydrogen, the ionization state of these regions was therefore dependent on the local source population. If it is true that quasars were responsible for the reionization of helium, then these are much rarer sources than the galaxies responsible for the reionization of hydrogen. As a result there would be large fluctuations in the HeIII reionization redshift due to Poisson fluctuations in the number of sources and variations in the opacity of the IGM (Reimers et al. 2006). These fluctuations would not be simply related to the local large scale overdensity. On the other hand, the arguments regarding the fluctuations in the redshift of hydrogen reionization due to enhanced structure formation in overdense regions must also apply to the reionization of helium, and these will be present in addition to the Poisson noise. As already mentioned, the delay in reionization due to an overdensity δ is not a function of cosmic time. Thus we see from equation (10) that since the delay is also independent of collapsed fraction (which we expect to be different for hydrogen and helium reionization), the delay (δz) in the redshift of HeIII reionization for a particular value of the comoving overdensity δ is equal to the delay for the reionization of hydrogen. As a result, in an overdense region both hydrogen and helium would be reionized early by the same offset in redshift. The large-scale variations in the reionization redshifts of hydrogen and helium lead to a different accretion histories for galaxies, which in-turn lead to different star-formation histories, and thus a change in the luminosity of a galaxy given a total stellar mass due to the different age distribution of the stellar population.

Before proceeding, we draw attention to the approximation of sudden reionization in which the reionization of a volume on a scale R occurs at a redshift z . Of course some regions within that volume will have been reionized earlier. However our point is that, on average, a region of IGM will be reionized earlier by Δz within a volume of scale R . A critical component of our model is the assumption that the average variation in the redshift at which the gas that ultimately makes the progenitor galaxies was reionized is also equal to Δz .

Weinmann et al. (2007) have recently employed numerical simulations of reionization to compute whether a galaxy observed at the present time formed in a region of IGM prior to it being reionized, or whether it formed in a region that had already been reionized. In their work the time of formation of a galaxy refers to the identification of the earliest progenitor of the local galaxy above the resolution limit of the simulation. These authors find that more massive galaxies had progenitors that formed in neutral regions while less

massive galaxies formed in ionized regions. They also conclude that there is no correlation between the reionization history of field galaxies and their environment or large scale clustering (however see discussion below). While very useful in understanding the relation between the early formation histories of galaxies and the reionization process, these findings are not directly applicable to our discussion, which aims to calculate the average effect of reionization on all the progenitors of a low redshift galaxy rather than on its earliest progenitor.

But interestingly, the numerical results presented by Weinmann et al. (2007) show consistency with the quantitative expectations of our simple model. Their Figure 6 shows the relation between the reionization redshift for a massive galaxy and the local overdensity of massive galaxies within 10 comoving Mpc. The simulations predict a large scatter of ± 1 redshift unit about a mean relation that varies by $\Delta z \sim 0.8$ between present-day galaxy overdensities of -1 and 1 on 10 comoving Mpc (cMpc) scales, with overdense environments reionizing at higher redshift. While the scatter is large as expected, the statistical accuracy of the measured mean is significantly below $\Delta z = 0.8$ due to the large sample size of model galaxies. This implies that Weinmann et al. (2007) do indeed infer a relation between large scale environment and the mean reionization redshift, but that the variation in the mean relation is not significant with respect to the scatter among individual galaxies. We can compare the mean relation of Weinmann et al. (2007) for the reionization redshift of the earliest progenitor from simulations with expectations from our simple model for patchy reionization. On a scale of 10 cMpc, the variance in the density field at $z = 0$ is $\sigma(10\text{cMpc}) \sim 0.8$. Since the bias is around $b \sim 1.1$ for the $5 \times 10^{12} M_\odot$ galaxies from which the simulated relation was calculated, we expect 1-sigma fluctuations in the overdensity of galaxies at $z = 0$ on 10 cMpc scales to be ± 1 . Thus the numerical simulations of Weinmann et al. (2007) predict fluctuations in the reionization redshift around a mean of $z \sim 8.5$ (predicted by their model) of $\delta z \sim 0.4$ for the earliest progenitor of massive local galaxies. Our simple model predicts the fluctuation in the reionization redshift of the IGM with an overdensity of $\delta \sim 0.8$ to be $\delta z \sim (1+z) \times (\delta D(z))/\delta_c \sim 0.6$, where D is the growth factor (from equation 10). This number is similar to the typical fluctuations in the reionization redshift of the earliest progenitor in the simulations of Weinmann et al. (2007). Weinmann et al. (2007) also argue that the way in which a galaxy is reionized (either externally or internally) is not sensitive to the local overdensity of galaxies. Thus numerical simulations predict that the process of reionization is similar in overdense and underdense regions, but that reionization is accelerated in overdense regions. These findings from numerical simulation support the basic assumptions of our simple model.

5.2 Model of Reionization induced bias

To develop our model we consider a galaxy residing in a halo of mass M at $z \ll z_{\text{reion}}$. This galaxy has accreted its mass via a merger tree, which we generate using the method described in Volonteri, Haardt & Madau (2003). We describe this tree as having a number $N_{\text{halo}}(z_j)$ of halos of mass $M_i(z_j)$ at redshift z_j , where the number of redshift

steps is N_z , with values of redshift that increase from the redshift of the primary halo in the tree so that $z_0 = z$. These halos grow in mass due to mergers of progenitor halos, and due to accretion (which, in the Press-Schechter formalism, is the sum of mergers with halos below the resolution limit of the merger tree).

First consider halos above the minimum mass for star formation (which is either M_{cool} in neutral regions, or M_{reion} in reionized regions respectively). At each redshift step, a fraction of the baryonic mass gained by these halos through accretion is turned into stars, thus

$$\begin{aligned} \Delta M_{*,i}(z_j) &= f_* \frac{\Omega_b}{\Omega_m} (M_i(z_j) - M_i(z_{j+1})) \quad \text{for } M > M_{\text{min}} \\ \Delta M_{*,i}(z_j) &= 0 \quad \text{otherwise,} \end{aligned} \quad (11)$$

where f_* is the star formation efficiency. We choose $f_* = 0.3$ throughout this paper, though our conclusions are not sensitive to this choice.

In addition, we assume that whenever a progenitor halo i at redshift z_j in the merger tree crosses the minimum mass for star formation through the merger of two sub-units $M_{i,1}(z_{j+1})$ and $M_{i,2}(z_{j+1})$, stellar mass is added in the amount

$$\Delta M_{*,i}(z_j) = \left(f_* \frac{\Omega_b}{\Omega_m} M_i(z_j) \right) - (M_{*,i,1}(z_{j+1}) + M_{*,i,2}(z_{j+1})), \quad (12)$$

where $M_{*,i,1}(z_{j+1})$ and $M_{*,i,2}(z_{j+1})$ are the stellar mass content of the progenitors prior to the merger. Similarly, whenever a progenitor halo i at redshift z_j in the merger tree crosses the minimum mass for star formation through accretion, stellar mass is added in the amount

$$\Delta M_{*,i}(z_j) = f_* \frac{\Omega_b}{\Omega_m} M_i(z_j) - M_{*,i}(z_{j+1}), \quad (13)$$

where $M_{*,i}(z_{j+1})$ is the stellar mass content of the halo at the previous redshift step. The subtraction of the second term is necessary in each of the latter cases because the minimum mass in a region increases suddenly at the local reionization epoch. The total stellar mass added at each step is the sum of these three contributions. We may then construct a stellar-mass accretion history

$$\frac{d(\Delta M_*)}{dz}(z_j) \sim \frac{1}{z_j - z_{j-1}} \sum_{i=0}^{N_{\text{halo}}(z_j)} \Delta M_{*,i}(z_j). \quad (14)$$

Our scheme neglects any star formation that may occur in recycled gas following a major merger. However star formation in recycled gas at low redshift is by definition already above the minimum threshold for star-formation and so should not be sensitive to the local redshift of reionization. We have used a sudden transition of the minimum virial temperature for star formation, rather than the more gradual transition described by the filtering mass, which takes account of the formation time-scale for a collapsing halo and the full thermal history of the IGM. In the hierarchical build-up of a halo, the merger of collapsed progenitors, combined with accretion of mass onto these progenitors can be identified with the formation of the final halo within the spherical collapse model and Press-Schechter formalism. The sudden transition of virial temperature is therefore the appropriate choice for our model since the star formation is calculated to coincide with the formation of a halo during a merger tree. The fraction of mass in the halo at redshift z that was

already collapsed prior to reionization is therefore explicitly accounted for in our model.

Before proceeding we note that the calculation of the merger tree is independent of the large-scale overdensity δ . We demonstrate this explicitly in Appendix A, for a cosmology that ignores the cosmological constant (as is appropriate at high redshift). Thus, to estimate the additional contribution to the bias that is due to changes in the star formation history associated with the reionization variable redshift, we may compute one merger tree within the mean background cosmology, and then change only the reionization redshift to account for the overdensity of the region in which the parent halo formed. The total bias for the observation of this galaxy is then the reionization induced bias computed from this merger tree, plus the usual galaxy bias. This independence of the merger tree on δ greatly simplifies calculation of the dependence of the apparent brightness of a galaxy within a halo of mass M on the large-scale overdensity.

We next compute the spectrum of stellar light that results from this star formation history using the stellar population model of Leitherer et al. (1999). We assume a 1/20th solar metallicity population with a Scalo (1998) mass-function and begin with the time dependent spectrum for a burst of star formation². This yields the emitted energy per unit time per unit frequency per solar mass of stars $d^2\epsilon_\nu/dtdM(t_0 - t_j)$ at a time $t_0 - t_j$ following the burst, where t_0 and t_j are the ages of the universe at the redshift of the primary halo (z_0) and z_j respectively. The flux (erg/s/cm²/Hz) from the galaxy at z then follows from the sum over the starburst associated with each star formation episode. We find

$$f_\nu = \sum_{j=0}^{N_z} \Delta M_\star(z_j) \frac{d^2\epsilon_\nu}{dt dM}(t_0 - t_j) \frac{1}{4\pi D_L(z_0)^2} (1 + z_0), \quad (15)$$

where D_L is the luminosity distance at z . We note that our scheme neglects enrichment of gas prior to star formation, so that all star-bursts are assumed to have the same metallicity. Since we are not computing the contribution from star-formation in recycled gas, we do not expect this assumption to have a large influence on our results. Moreover, the UV spectra of galaxies are very sensitive to the dust content of a galaxy and therefore also sensitive to the metallicity. However the reionization bias would be sensitive to the ratio of fluxes in which the effect of the dust on a single spectrum will vanish.

We can then use equation (15) to compute the spectra for two star-formation histories that correspond to the mean universe and to an overdensity δ , with reionization redshifts separated by δz . These spectra in turn allow us to determine ratio of fluxes and hence to compute a value of $\mu(\delta)$. As described above, in order to compute the contribution of reionization to galaxy bias we make this comparison directly, using the same merger tree with different values of the reionization redshift to obtain different star formation histories.

Equation (15) implies that the apparent flux of a galaxy will be sensitive to its star-formation history, which will in turn be sensitive to the redshift of reionization. We would

now like to calculate the typical flux change induced by the effect of a large scale overdensity on the reionization redshift. In order to achieve this we must determine the change in flux as a function of scale, and at a range of overdensities. As shown above, the delay in the reionization redshift is proportional to the variance of the power-spectrum on the scale of interest. Since the variance decreases towards large scales, we find that the fluctuations in reionization redshift should also be smaller on large scales. In order to investigate the scale dependence of the bias, we could therefore compute the difference in star formation histories corresponding to different delays in reionization over a number of spatial scales. However we find that for individual merger trees, the value of the apparent magnitude change (i.e. the logarithm of the observed flux) is approximately proportional to the delay in reionization. Thus we can estimate the change in magnitude due to reionization using a first order expansion in δz

$$\begin{aligned} 2.5 \log_{10} \mu &= 2.5 \frac{d \log_{10}[f_\nu(z_{01})]}{dz_{01}} \delta z \\ &\sim 2.5 \log_{10} \left[\frac{f_\nu(z_{01})}{f_\nu(z_{01} + \Delta z)} \right] \frac{\delta z}{\Delta z}, \end{aligned} \quad (16)$$

where z_{01} is the overlap (reionization) redshift, which we assume to be $z = 6$ throughout this paper (e.g. White et al. 2003; Fan et al. 2006), and $\Delta z = 0.25$ is the separation in overlap redshifts of the two star formation histories computed for each merger tree. Thus the magnitude change can be computed for a single length scale R and overdensity δ , and then translated to other length scales and overdensities in proportion to the variance. We employ this approximation which greatly simplifies our calculations.

Given a scale R and variance $\sigma(R)$ we can now estimate the contribution of reionization to galaxy bias. For each merger tree k , we compute the bias averaged over likelihoods at each δ in the density field

$$b_{\text{reion},k} = \frac{1}{\sqrt{2\pi}\sigma(R)} \int d\delta \left[\frac{1 - \mathcal{L}(\delta)}{\delta} \right] \exp\left(-\frac{\delta}{2\sigma(R)}\right)^2. \quad (17)$$

To get the average bias for the galaxy population, we then average the bias evaluated using N_{trees} different merger trees,

$$b_{\text{reion}} = \frac{1}{N_{\text{trees}}} \sum_{k=0}^{N_{\text{trees}}} b_{\text{reion},k}. \quad (18)$$

In the remainder of this paper, we use the above model to estimate the contribution of reionization to galaxy bias for several existing and planned galaxy surveys.

6 LY-BREAK GALAXIES

As a first application of our model we construct mock spectra corresponding to Ly-break galaxies (Steidel et al. 2003) at $z = 3$. Examples of the model star formation history and resulting galaxy spectra are shown in Figure 1 assuming a halo mass of $M = 10^{12} M_\odot$ (Adelberger et al. 2005). Here we include only hydrogen reionization as the mechanism that introduces fluctuations in the star-formation history.

In the upper left panel of Figure 1 we show an example of the star formation rate summed over all halos that end up as part of the galaxy in a $10^{12} M_\odot$ halo at $z = 3$. Here

² Model spectra of star forming galaxies obtained from <http://www.stsci.edu/science/starburst99/>.

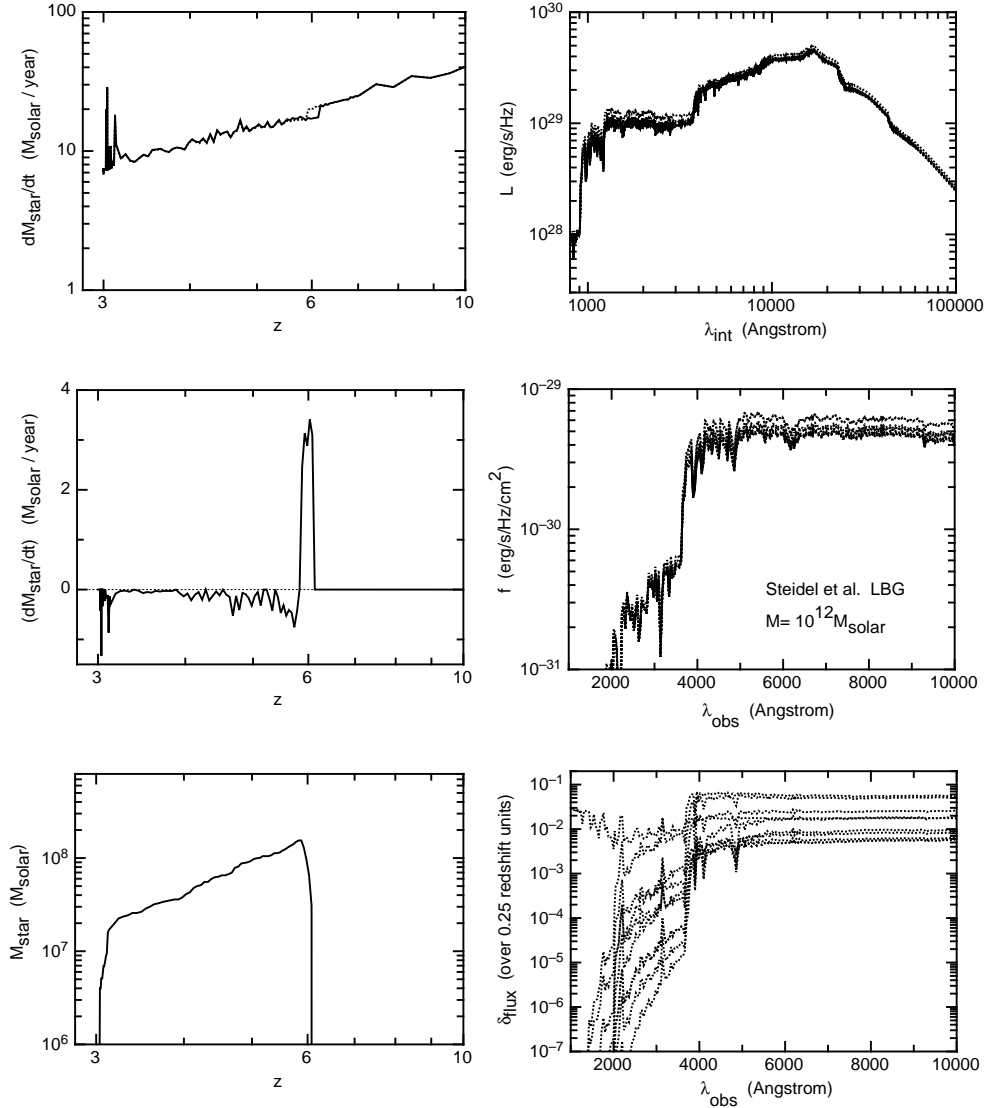


Figure 1. The effect of reionization on the star formation histories of galaxies. These examples correspond to typical Ly-break galaxies at $z = 3$ in the survey of Steidel et al. (2003). *Upper Left:* The star formation rate summing over all halos that end up as part of the galaxy in a $10^{12} M_{\odot}$ halo at $z = 3$. The solid and dotted lines refer to histories where overlap occurred at $z = 6.125$ and $z = 5.875$ respectively. *Central Left:* The difference in star formation rate for the two histories. *Lower Left:* The difference in cumulative stellar mass for the two histories. *Upper Right:* Rest frame luminosity of ten example Ly-break galaxies at $z = 3$. *Central Right:* Observed flux (including Ly α absorption) for the ten example galaxies. *Lower Right:* The magnitude change induced by a delay in reionization of 0.25 units of redshift.

the solid and dotted lines refer to histories where the overlap of ionized regions occurred at $z = 6.125$ and $z = 5.875$ respectively. The effect of the reionization redshift on these star formation histories is more easily seen in the central left panel where we plot the difference in star formation rate between the two histories. Figure 1 shows that early reionization initially results in a deficit of star formation. This deficit is then made up continually until $z = 3$. By $z = 3$ the total stellar mass is the same for both histories ($M_{\star} = f_{\star} \Omega_b / \Omega_m M$) as required for consistency of the model. This behavior is also demonstrated in the lower left panel of Figure 1 where we plot the difference in cumulative stellar mass, summing over all halos that end up as part of the primary galaxy at $z = 3$.

Figure 1 also shows examples of the resulting galaxy

spectrum. In the upper right panel we show the rest frame luminosity for ten example $10^{12} M_{\odot}$ galaxies at $z = 3$. In each case reionization was at $z = 6.125$. The differences between these spectra arise due to the slightly different age distribution of the stellar populations that result from the stochastic buildup of mass in the merger tree. In the central right panel of Figure 1 we show the corresponding observed flux [including mean Ly α absorption, see e.g. Fan et al. (2006)] for the same ten example Ly-break galaxies at $z = 3$. The distinctive Ly-break near 4000 \AA is clearly visible in these spectra. Finally, in the lower right hand panel we show the fractional change (δ_{flux}) in the observed flux that is induced by a delay in reionization of $\Delta z = 0.25$ units of redshift. This flux change, which is related to the parameter μ through equation (16) corresponds to differences in the

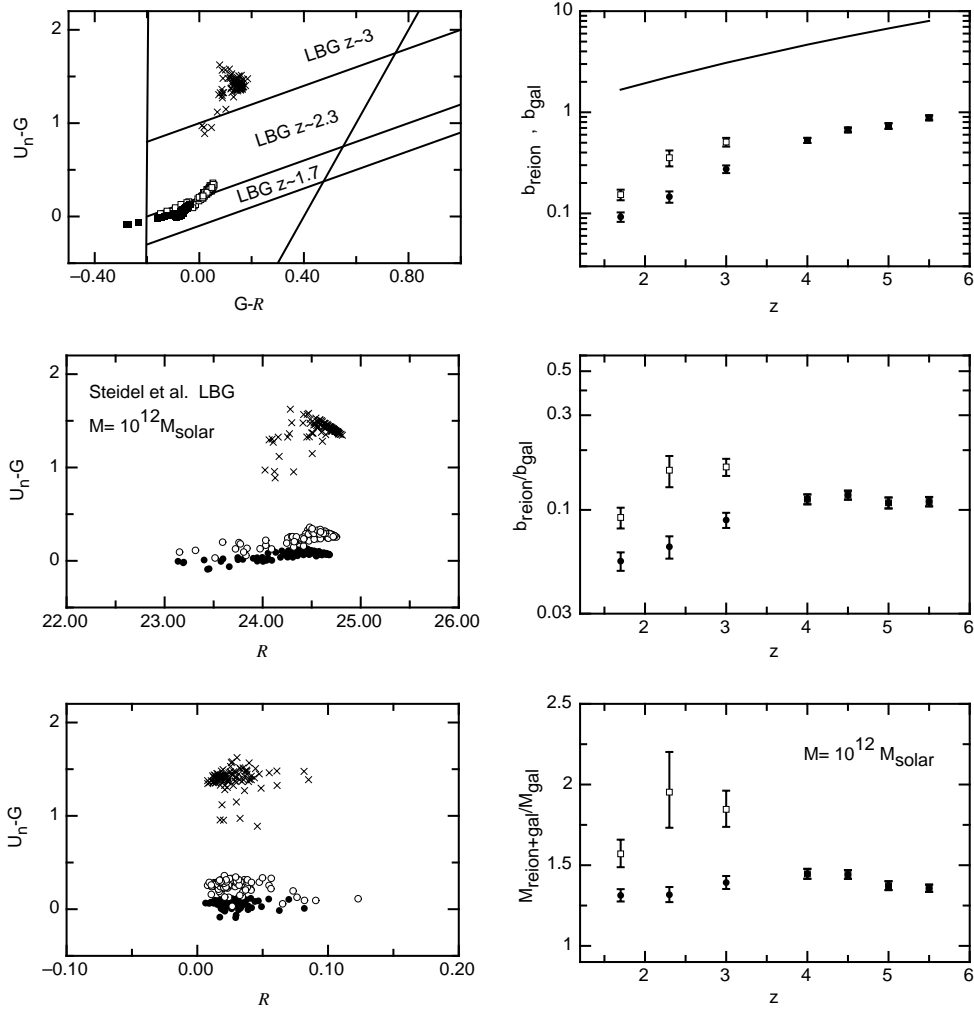


Figure 2. Examples of clustering bias in Ly-break galaxies induced by reionization. *Upper Left:* The primary color selection (Steidel et al. 2003) for LBGs at $z \sim 1.7$ (solid points), $z \sim 2.3$ (open points) and $z \sim 3$ (crosses). *Central Left:* The apparent magnitudes and colors of the model galaxies. *Lower Left:* The $U_n - G$ color as a function of the change in R -band magnitude induced by reionization. *Upper Right:* The bias introduced by reionization in cases where helium reionization at $z \sim 3.5$ is considered in addition to hydrogen reionization (open squares) and where it is not (solid squares). The bias was computed assuming a flux evaluated at a rest-frame wavelength of 1350\AA within a 400\AA window. The galaxy bias is shown by the solid line for comparison. The error bars represent the statistical noise in the simulations due to the finite number of merger trees. *Central Right:* The ratio of the component of bias introduced through reionization to the usual galaxy bias. *Lower Right:* The factor by which the mass will be overestimated in clustering analyses where reionization is not considered.

star-formation histories that are comparable to the example shown in the left hand panels of Figure 1. The fluctuations are at the level of a few tenths to a few percent. We investigate the bias that arises from the resulting values of μ in § 6.2.

6.1 The colors of simulated Ly-break galaxies

Our aim in this paper is to evaluate the importance of reionization with respect to galaxy bias in measurements of galaxy clustering. To this end we have constructed model star-formation histories that include the effect of reionization, and computed the effect of reionization on the corresponding model galaxy spectra. In order for our results to be applicable to surveys of real galaxies, we must, at a minimum demonstrate that our model produces realistic spectra

with colors that would see the model galaxies selected into the survey of interest. Therefore, before describing our results for the reionization induced bias we demonstrate that our model galaxies have colors and magnitudes that correspond to those of real Ly-break galaxies (LBG).

In the upper left panel of Figure 2 we show the position of 100 model Ly-break galaxies within the primary color selection³ (Steidel et al. 2003) for LBGs at $z \sim 1.7$

³ To estimate the colors of Ly-break galaxies we assume top-hat filters of central wavelength λ_0 and width $\Delta\lambda$ to approximate the filter set used in Steidel et al. (2003). We use AB -magnitudes throughout this paper. The filters have $(\lambda_0, \Delta\lambda) = (3550, 600)$ for the U_n -band; $(\lambda_0, \Delta\lambda) = (4780, 1100)$ for the G -band; $(\lambda_0, \Delta\lambda) = (6830, 1250)$ for the R -band; $(\lambda_0, \Delta\lambda) = (8100, 1650)$ for the I -band.

(solid points), $z \sim 2.3$ (open points) and $z \sim 3$ (crosses). The galaxies at $z \sim 3$ are well separated from those at lower redshift due to the Ly-break moving to a wavelength beyond the U_n -band. Our model galaxies at $z \sim 1.7$ and 2.3 have similar colors that are close to the selection cutoff. This is consistent with the observed galaxies, which have overlapping redshift distributions when selected via this criteria (Adelberger et al. 2005). For their clustering analysis Adelberger et al. (2005) restricted themselves to objects with $23.5 < \mathcal{R} < 25.5$. In the central left panel we show the position of our model galaxies in a color-magnitude diagram. The apparent magnitudes of these model galaxies are consistent with the observed population. Thus our model produces Ly-break galaxies with both the correct colors, and the correct luminosity. Finally we check that reionization induced changes in the observed flux are not sensitive to the observed galaxy color. In the lower left panel of Figure 2 we show the $U_n - G$ color as a function of the change in \mathcal{R} magnitude induced by reionization. We find no systematic trend of the flux variation with galaxy color.

6.2 Reionization induced bias for Ly-break galaxies

We now present an estimate for the reionization induced bias in the sample of Ly-break galaxies. We show results at a scale of $R = 10$ comoving Mpc, which is a factor of ~ 3 larger than the clustering length at $z \sim 3$ (Adelberger et al. 2005). We evaluate the bias for fluxes measured at a rest frame wavelength of 1350\AA , and within a 400\AA wide band (this choice allows us to compare the predicted bias over the redshift range $1.7 < z < 5.5$). In the upper right panel of Figure 2 we show the bias introduced by reionization in cases where hydrogen reionization alone is considered (solid squares), as well as cases where helium reionization at $z \sim 3.5$ is considered in addition to hydrogen reionization (open squares). Also shown for comparison is the galaxy bias due to enhanced structure formation (solid line). In this figure the error bars represent the statistical noise in the simulations due to the finite number of merger trees. In order to better see the relative contributions of enhanced structure formation and reionization induced galaxy bias, in the central right panel we show the ratio of the component of bias introduced through reionization to the usual galaxy bias. Reionization represents a 10-20% correction to the galaxy bias in Ly-break galaxy samples at $1.7 \lesssim z \lesssim 3$. This correction corresponds to a predicted amplitude for the galaxy correlation function that can be 50% larger than the prediction in the absence of consideration of reionization. Thus reionization provides a correction to the clustering amplitude that is in excess of the observational error for the existing Ly-break galaxy samples at $1.7 \lesssim z \lesssim 3$.

One of the primary uses for measurements of clustering in a galaxy sample is the estimation of host halo mass. This mass estimate is made by measuring the bias, which is then interpreted theoretically in terms of host mass. However the results summarized in Figure 2 suggest that existing estimates of the galaxy bias could be systematically in error, at a level significantly larger than the observational error, due to the neglect of the effect of reionization. This in turn implies that estimates of the host masses in galaxy samples are also systematically in error. To evaluate the importance

of this systematic error, we estimate the ratio of the inferred host masses with and without the inclusion of reionization, yielding

$$\ln(M_{\text{reion+gal}}) - \ln(M_{\text{gal}}) \approx \frac{d \ln(M)}{db} [(b_g + b_{\text{reion}}) - b_g], \quad (19)$$

or

$$\frac{M_{\text{reion+gal}}}{M_{\text{gal}}} \approx \exp \left[b_{\text{reion}} \frac{d \ln M}{db} \right], \quad (20)$$

where dM/db is evaluated via equation (5). The factor by which the mass will be overestimated in clustering analyses where reionization is not considered is plotted in the lower right hand panel of Figure 2. We find that masses in existing Ly-break galaxy surveys (Adelberger et al. 2005) have been overestimated by factors of between 1.5 and 2.

In addition to showing results evaluated at redshifts corresponding to the Ly-break galaxy sample, we also show results for hypothetical galaxy samples $4 \leq z \leq 5.5$. At these redshifts helium is not doubly reionized, and so all modifications to the star formation history are due to the reionization of hydrogen at $z \sim 6$. This is in contrast to samples at $z \lesssim 3$ where helium reionization is complete. Figure 2 demonstrates that we expect to see a significant jump in the amplitude of the clustering for galaxy samples of fixed absolute magnitude following the double reionization of helium at $z \sim 3.5$.

Up to this point we have presented results for $R = 10$ comoving Mpc. We do not explicitly show results corresponding to other length scales in this paper for the following reason. On the scales of interest ($\sim 3 - 100$ cMpc), the variance is approximately a power-law with R , while the mass function is approximately a power-law with $\log(M)$. It turns out that these power-laws approximately cancel, leaving the bias induced by reionization almost independent of scale. This independence is a coincidence. A different slope of the primordial power-spectrum would have led to a scale dependent bias. However the conclusion that the bias is not scale dependent should be treated with caution for two reasons. First, we are unable to rule out scale dependence at the level of a few percent at the numerical accuracy of our simulations. Second, as discussed in § 8.2, the scale-independence might be broken by additional astrophysical effects. Thus, future observations aiming to measure clustering at the percent level over a large range of spatial scales will need to carefully account for this possibility.

6.3 Mass dependence of the reionization bias

Thus far our discussion of Ly-break galaxies has assumed a halo mass of $10^{12} M_\odot$, corresponding to observed Ly-break galaxies. In this section we describe the dependence of the predicted reionization induced galaxy bias on the halo mass. In Figure 3 we show examples of the clustering bias in Ly-break galaxies induced by reionization for halo masses of $M = 10^{11} M_\odot$ and $10^{13} M_\odot$. In the left hand panels we show the bias introduced by reionization in cases where helium reionization at $z \sim 3.5$ is considered in addition to hydrogen reionization (open squares) and where it is not (solid squares). As before the bias was computed assuming a flux evaluated at a rest-frame wavelength of 1350\AA within a 400\AA window. The usual galaxy bias is shown by the solid line for

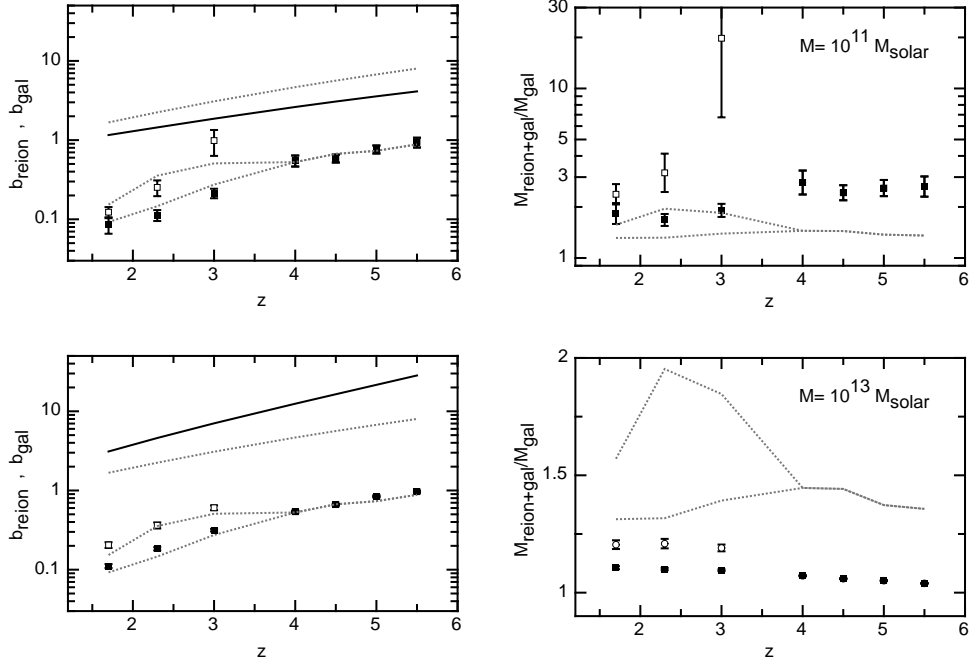


Figure 3. Examples of clustering bias in Ly-break galaxies induced by reionization as a function of the halo mass. *Left Hand Panels:* The bias introduced by reionization in cases where helium reionization at $z \sim 3.5$ is considered in addition to hydrogen reionization (open squares) and where it is not (solid squares). The bias was computed assuming a flux evaluated at a rest-frame wavelength of 1350\AA within a 400\AA window. The galaxy bias is shown by the solid line for comparison. The error bars represent the statistical noise in the simulations due to the finite number of merger trees. *Right Hand Panels:* The factor by which the mass will be overestimated in clustering analyses where reionization is not considered. Results are shown for two halo masses, $M = 10^{11} M_{\odot}$, and $M = 10^{13} M_{\odot}$. In each case the corresponding results for $M = 10^{12} M_{\odot}$, as presented in Figure 2, are shown for comparison (light lines).

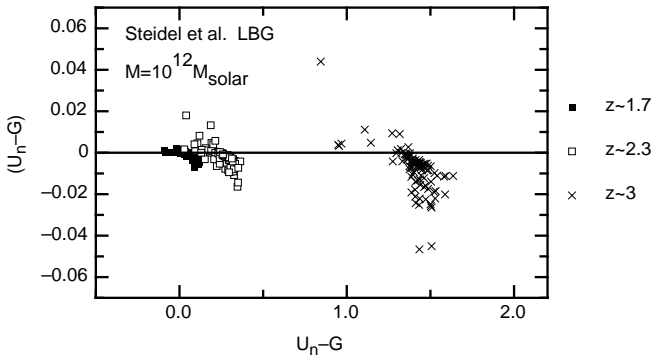


Figure 4. Examples of how reionization will effect the observed colors of Ly-break galaxies. The figure shows the change in $U_n - G$ color for LBGs at $z \sim 1.7$ (solid points), $z \sim 2.3$ (open points) and $z \sim 3$ (crosses), due to a fluctuation in the reionization redshift of $\delta z = 0.25$.

comparison. In addition, in each case the corresponding results for $M = 10^{12} M_{\odot}$, as presented in Figure 2, are shown for comparison (light lines).

We find that the contribution to the bias due to reionization is fairly insensitive to the halo mass. To understand this we note that although we would expect the larger halos to have begun forming earlier, and so to have their star formation histories less effected by the reionization of the IGM, this is offset by the steeper mass function of massive halos. On the other hand the galaxy bias due to enhanced struc-

ture formation in over dense regions is quite sensitive to the halo mass, and so we find that the fractional contribution to the galaxy bias is smaller for more massive systems. As a result, the systematic error introduced into the estimate of halo mass from clustering amplitude is less serious for more massive systems. In the right hand panels of Figure 3 we show the factors by which the mass will be overestimated in clustering analyses where reionization is not considered. While halos with masses near $M \sim 10^{11}$ would be incorrectly inferred by a factor that could be larger than 3, the systematic error on very massive systems of $M \sim 10^{13} M_{\odot}$ would be at only a level of 10s of percent. This implies that the reionization bias will become more important as future surveys begin to discover populations of less massive galaxies at high redshift.

6.4 Reionization and the observed colors of Ly-break galaxies

The reionization induced bias should be sensitive to the selection band. In the case of Ly-break galaxies, we would therefore expect that the clustering amplitude would be sensitive to the band in which the flux selection was performed. Alternatively, overdense regions would therefore be expected to have a slightly bluer population of galaxies.

In Figure 4 we show the change in $U_n - G$ color for LBGs at $z \sim 1.7$ (solid points), $z \sim 2.3$ (open points) and $z \sim 3$ (crosses), due to a fluctuation in the reionization redshift of $\delta z = 0.25$. Galaxies in overdense regions, have systemati-

cally bluer colors due to their younger stellar populations. The example shown for Ly-break galaxies has fluctuations in $\Delta(U_n - G)$ color at the $\sim 0.01 - 0.02$ level given a fluctuation in the redshift of overlap amounting to $\delta z = 0.25$ redshift units. On a scale of 10 comoving Mpc, the fluctuation in the overlap redshift around a mean of $z = 6$ is $\langle(\delta z)^2\rangle^{1/2} \sim 0.6$ (from equation 10). Hence the expected color variation between overdense and under dense regions would be $\Delta(U_n - G) \sim 0.03 - 0.05$ magnitudes. This expected correlation between galaxy color and overdensity would be evidence for the reionization induced galaxy bias, and could be used to calibrate its effect empirically.

This systematic variation in color is much smaller than the range of colors in the observed samples. However high redshift samples are selected to be redder than a certain limit. In practice one would therefore have to be careful that the systematically bluer colors did not bias the sample *against* finding galaxies in overdense regions. At the redshifts of LBGs, the shift of the Ly-break with redshift primarily effects both the $U_n - G$ and $G - R$ colors. As a result, LBGs are selected to lie above a line with positive gradient in the $(U_n - G) - (G - R)$ color-color space. We note that like reddening, the reionization induced color change will be in both bands, and will therefore transform the position of the galaxy in color-color space in a direction parallel to the selection criteria for LBGs. As a result, we do not expect the reionization induced color change to introduce a bias through the survey selection criteria.

7 SURVEYS FOR BARYONIC OSCILLATIONS

We next apply our model to surveys that aim to measure baryonic acoustic oscillations in the clustering of galaxies at $z < 1$. These surveys require exquisite accuracy of the clustering amplitude, and so the effect of reionization on galaxy bias could be particularly important. We consider two surveys, the existing SDSS Luminous Red Galaxy survey, and the planned WiggleZ survey.

7.1 Luminous Red Galaxies

First we discuss the effect of reionization on the star formation histories of SDSS Luminous Red Galaxies (LRG) at $z = 0.3$ (Eisenstein et al. 2001). By selection, LRGs are old galaxies with passively evolving stellar populations and no recent star formation. Thus, in order to model LRGs at $z \sim 0.3$ we arbitrarily shut off star formation in the galaxies at $z = 1$. The spectrum of the galaxy is not sensitive to the exact choice of redshift where star formation is curtailed, provided that the population of massive stars from the most recent star-burst have already died. However a cutoff in star formation is necessary if the models are to reproduce the correct colors of the observed sample.

The upper and lower left hand panels of Figure 5 show the primary color selection⁴ (Eisenstein et al. 2001) for

LRGs at $z \sim 0.3$. The model produces galaxies with the correct colors and observed flux, as is illustrated by the magnitudes and colors of the 100 modeled galaxies which are also plotted in the left hand panels of Figure 5. In the upper right hand panel of Figure 5 we show examples of observed flux (including Ly α absorption) for ten model LRGs at $z = 0.3$. These spectra show less variation than those of the Ly-break galaxies discussed in the previous section. This lack of variation is a feature of the LRG sample. Due to the lack of star formation in these galaxies, the spectra do not exhibit a sharp Ly-break. In the lower right panel of Figure 5 we show the fractional change in flux induced by a delay in reionization of 0.25 units of redshift. We see that reionization has a very small effect on the observed flux of these galaxies. The resulting value of bias is quoted in the upper right panel. LRGs are selected to lie within a range of rest-frame absolute r -magnitudes, and we therefore calculate the bias at the rest-frame r -magnitude. Reionization will decrease the bias by $\sim 0.1\%$ in the LRG sample, and therefore the clustering amplitude by $\sim 0.2\%$. Also shown is the fractional systematic error in the derived host mass ($\sim 1\%$).

Eisenstein et al. (2005) summarize the various corrections to the linear bias that have been previously considered when interpreting clustering data, including those due to non-linear gravity, and coupling of gravitational modes. On scales larger than ~ 40 comoving Mpc, the sum of previously considered corrections drops below the 1% level. For this reason among others, the correlation function of galaxies is considered to be a very clean tracer of the underlying large-scale mass-distribution, and in particular a perfect sample with which to investigate the baryonic oscillations in the matter power-spectrum (Eisenstein et al. 2005). It is therefore important to note that while the correction to the galaxy bias due to reionization predicted by our models is at a very low level for the LRG sample, it may nevertheless be comparable to the largest correction to linear theory yet described on the scales relevant to baryonic oscillation experiments. On the other hand, our model predicts no dependence of the reionization induced bias on scale. As a result it is very unlikely that the details of the reionization will adversely effect attempts to use the measurements of baryonic acoustic oscillations as a cosmic standard ruler (Blake & Glazebrook 2003). We return to this point in § 8.2.

7.2 Blue Star Forming Galaxies

For our second example we consider the effect of reionization on the star formation histories of galaxies that will be selected by the WiggleZ Survey (Glazebrook et al. 2007) at $z = 0.8$. Unlike the SDSS LRG sample considered in the previous section, galaxies in the WiggleZ survey will be selected as being star forming via the Ly-break using observations in the near and far UV in addition to optical colors. In modeling these galaxies we therefore do not impose a cutoff in the star formation prior to the observed redshift.

The upper and lower left hand panels of Figure 6 show

⁴ To estimate the colors of LRGs in this paper, we assume top-hat filters of central wavelength λ_0 and width $\Delta\lambda$ to approximate the Sloan Digital Sky Survey filter set. The filters have $(\lambda_0, \Delta\lambda) =$

$(3543, 564)$ for the u -band; $(\lambda_0, \Delta\lambda) = (4770, 1388)$ for the g -band; $(\lambda_0, \Delta\lambda) = (6231, 1372)$ for the r -band; $(\lambda_0, \Delta\lambda) = (7625, 3524)$ for the i -band.

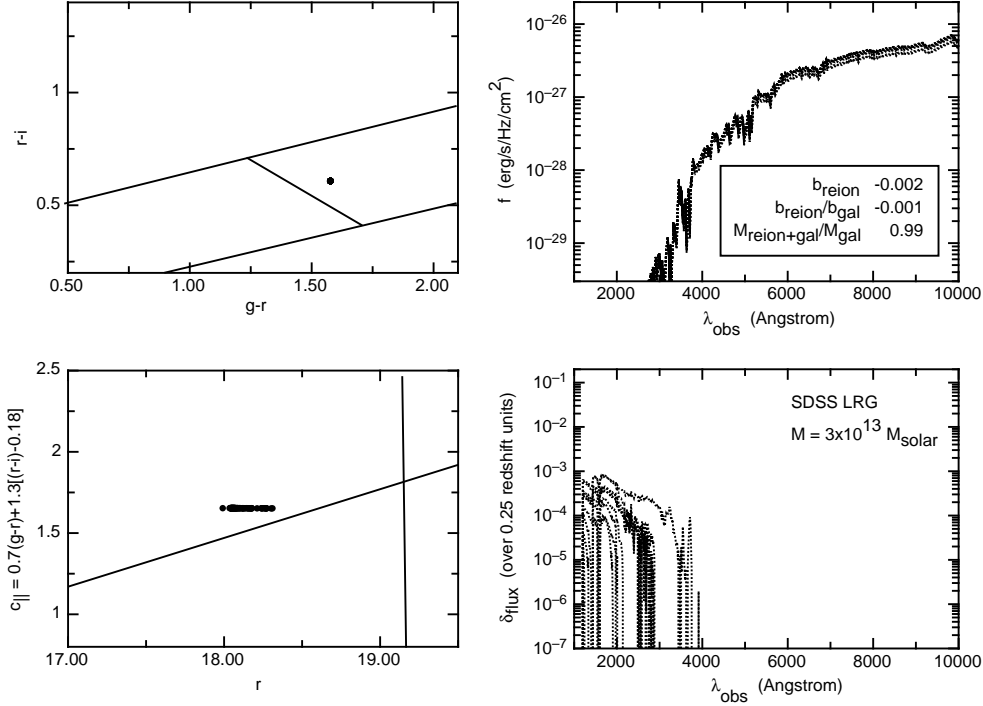


Figure 5. The effect of reionization on the star formation histories of galaxies. These examples correspond to typical SDSS Luminous Red Galaxies (LRG) at $z = 0.3$. *Upper and Lower Left:* The primary color selection (Eisenstein et al. 2001) for LRGs, together with the locations of our model galaxies. *Upper Right:* Observed flux (including Ly α absorption) for ten example the Ly-break galaxies at $z = 0.3$. *Lower Right:* The magnitude change induced by a delay in reionization of 0.25 units of redshift. The corrections to the bias due to reionization are quoted in the upper right panel. We compute this bias using the rest-frame r -magnitude.

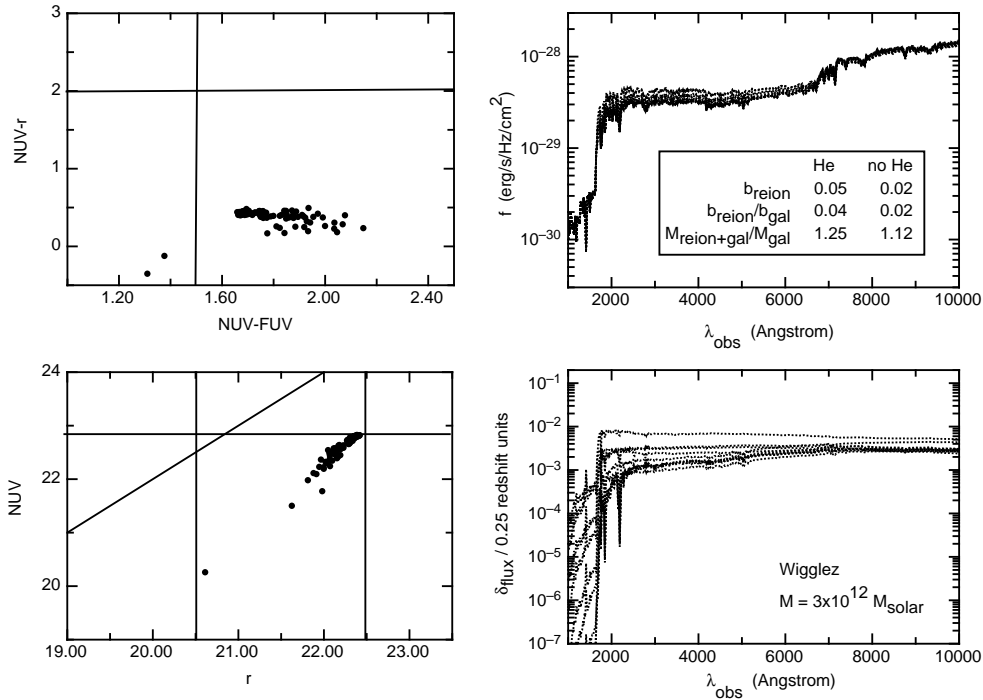


Figure 6. The effect of reionization on the star formation histories of galaxies that will be selected by the WiggleZ Survey (Glazebrook et al. 2007) at $z = 0.8$. *Upper and Lower Left:* The primary color selection (Glazebrook et al. 2007) for WiggleZ star forming galaxies at $z \sim 0.8$, together with the points for our model galaxies. *Upper Right:* Observed flux (including Ly α absorption) for ten example the Ly-break galaxies at $z = 0.8$. *Lower Right:* The magnitude change induced by a delay in reionization of 0.25 units of redshift. The corrections to the bias due to reionization are quoted in the upper right panel. This bias is computed at the observed r -band wavelength.

the primary color selection⁵ (Glazebrook et al. 2007) for WiggleZ star forming galaxies at $z \sim 0.8$. As with the previous examples the model produces galaxies with the correct optical and UV colors as well as the correct observed fluxes. In the upper right panel we show the observed spectra (including Ly α absorption) for ten examples of WiggleZ selected galaxies at $z = 0.8$. In the lower right hand panel of Figure 6 we show the fractional change in galaxy flux induced by a delay in reionization of 0.25 units of redshift. Unlike the LRG sample, the active star forming nature of the WiggleZ sample will mean that (like the Ly-break galaxies at higher redshift) patchy reionization is expected to significantly effect the observed clustering. The value of bias due to reionization, the relative correction to the galaxy bias from reionization, and the fractional change in the host mass inferred from the clustering amplitude are quoted in the upper right panel of Figure 6. We quote results based both on models that include only hydrogen reionization, and on models that also include the additional heating of the IGM due to double reionization of helium. The bias was calculated at the observed r -band wavelength to be consistent with the luminosity selection of the sample. Reionization will increase the bias by $\sim 5\%$ where helium reionization is included, and therefore the clustering amplitude by $\sim 10\%$. The mass estimate would be inferred incorrectly by a factor of as much as 25% where reionization is ignored.

One of the underlying premises motivating galaxy surveys to measure the baryonic acoustic oscillations is that the galaxies provide a nearly perfect *geometrical* estimate of the distance, free from any astrophysical complexities. However we have demonstrated that in the case of star forming galaxies at moderate redshifts, the astrophysical effect of reionization may enter the clustering statistics at the $\sim 5-10\%$ level. This level is significantly larger than the precision necessary for measurement of the baryonic acoustic oscillations. Moreover, it is important to note that the correction of $\sim 5\%$ to the galaxy bias due to reionization is the largest correction to linear theory yet described on the scales relevant to baryonic oscillation experiments (Eisenstein et al. 2005). On the other hand, as mentioned earlier, our simple model predicts that the bias due to reionization is, like the linear bias due to enhanced formation in overdense regions, independent of scale. Thus in an analysis that ignores reionization, the host mass would be misidentified, but because the correction to the linear bias is not scale-dependent, the unknown details of the reionization history may not compromise the measurement the baryonic acoustic peak.

8 DISCUSSION

Before concluding we discuss several issues which arise from our results and which will provide interesting areas for future research.

⁵ To estimate the UV colors in this paper, we assume top-hat filters of central wavelength λ_0 and width $\Delta\lambda$ to approximate the Galex filter set. The filters assumed have $(\lambda_0, \Delta\lambda) = (1550, 400)$ for the *FUV*-band; and $(\lambda_0, \Delta\lambda) = (2500, 1000)$ for the *NUV*-band.

8.1 Implications for the evolution of clustering in galaxy samples

The observed spatial correlation function of galaxies can be used to estimate the mass of the host dark-matter halo population through comparison with theoretical calculations. Having determined this mass, the evolution in the clustering of these galaxies can then also be computed and compared with the clustering properties of different populations at later times, with the aim of piecing together the evolution of the galaxy population. Moreover having estimated the host halo mass, the predicted number density of hosts can be compared with the observed number density of objects in order to obtain the fraction of halos containing a galaxy of the selected type at any one time. By comparing the inferred mass of LBGs from clustering data to the observed number counts, Adelberger et al. (2005) concluded that star formation in LBGs has a duty-cycle approaching unity. This conclusion is consistent with our star formation model in which nearly all model galaxies satisfy the LBG color selection criteria.

In this sub-section we consider the interpretation of LBG clustering evolution in light of the additional contribution to the observed galaxy bias from reionization. The spatial correlation function of dark matter halos as a function of radius r can be written in terms of the correlation function of dark-matter and the halo bias b as

$$\xi_h(r) = \xi_m b^2(M), \quad (21)$$

In practice this correlation function can be approximated using the parameterization

$$\xi_h \approx \left(\frac{r}{r_0} \right)^{-\gamma}, \quad (22)$$

where r_0 is defined as the clustering length, and $\gamma \sim 1.5$ describes the observed clustering of galaxies. More biased samples have larger clustering lengths.

We have argued that reionization will increase the observed value of the bias, by causing galaxies in overdense regions to have lower mass-to-light ratios due to their younger stellar populations. Thus we also expect reionization to increase the observed clustering length of a sample of galaxies at fixed halo mass. As a result, neglect of reionization leads to overestimation of the true clustering length for host dark-matter halos. For small values of $b_{\text{reion}}/b_{\text{gal}}$, equation (22) may be used to estimate the contribution to the observed clustering length ($\Delta r_{0,\text{reion}}$) that results from reionization induced bias using the expression

$$\begin{aligned} \Delta r_{0,\text{reion}} &\approx r_0 \frac{2}{\gamma} \frac{b_{\text{reion}}}{b_{\text{gal}}} \approx 1.25 r_0 \frac{b_{\text{reion}}}{b_{\text{gal}}} \\ &\approx 1.4 \left(\frac{r_0}{5.71} \right) \left(\frac{b_{\text{reion}}/b_{\text{gal}}}{0.2} \right), \end{aligned} \quad (23)$$

where the units of length-scales in the latter equality are comoving Mpc.

The clustering evolution of LBGs was discussed by Adelberger et al. (2005). They measure the clustering length of LBGs at $z \sim 1.7$, $z \sim 2.3$ and $z \sim 3$, obtaining $r_0 = 5.7$, $r_0 = 6.0$ and $r_0 = 6.4$ comoving Mpc respectively, corresponding to halo masses of $10^{12.1 \pm 0.2} M_\odot$, $10^{12 \pm 0.3} M_\odot$ and $10^{11.5 \pm 0.3} M_\odot$. Using simulations, Adelberger et al. (2005) calculated the clustering lengths that these galaxies should

have at lower redshifts of $z \sim 1$ and $z \sim 0.2$, and then compared these evolved clustering lengths to clustering studies of various populations of galaxies from other surveys. In particular, Adelberger et al. (2005) compared the evolved clustering length for LBGs to galaxies in the DEEP Survey (Coil et al. 2004), and in the Sloan Digital Sky Survey (Budavari et al. 2003). Adelberger et al. (2005) find that the LBG clustering length should evolve to a value that is consistent with redder elliptical galaxies ($r_0 \approx 9.4$ comoving Mpc at both $z = 1$ and $z = 0.2$), but which is larger than the clustering length for both the whole DEEP galaxy sample at $z \sim 1$ ($r_0 \approx 4.6$ comoving Mpc) and the blue Sloan Digital Sky Survey (SDSS) galaxies at $z = 0.2$ ($r_0 = 6.4$ comoving Mpc).

Based on these results Adelberger et al. (2005) argued that the descendants of LBGs will have clustering strengths that are significantly in excess of typical galaxies in optical magnitude-limited surveys at low redshift, and therefore that LBGs must have stopped forming stars before $z \sim 1$. However the results of this paper show that the clustering length at $z \sim 3$ has been overestimated by $\Delta r_{0,\text{reion}} \sim 1.5$ comoving Mpc. Since the reionization induced bias decreases in influence towards low redshift, and is small below $z = 1$ (see following sections) we conclude that, after accounting for the reionization induced bias, the clustering of the hosts of LBGs may well be comparable to the blue population of galaxies at $z < 1$. Indeed, as shown in Figure 13 of Adelberger et al. (2005), the value of $\Delta r_{0,\text{reion}}$ computed for LBGs at $z \sim 3$ is comparable to the difference in the clustering length of normal ellipticals and normal blue galaxies in the Sloan Digital Sky Survey at $z = 0.2$. Thus the effect of reionization on the observed clustering of galaxies should be accounted for in studies that aim to link galaxies at a range of epochs through the evolution of their clustering properties.

8.2 Helium reionization and scale dependent bias

The previous section (§ 7) ended with the positive suggestion that reionization will not impact measurement of the baryonic acoustic peak in samples of moderate redshift star-forming galaxies, due to the independence of the reionization induced bias on scale. Before concluding this paper, we describe an additional astrophysical situation which may compromise this favorable conclusion.

Our simple model predicts the bias introduced through reionization to be independent of scale. However this model ignores several astrophysical effects that could introduce additional fluctuations in temperature within the IGM, and hence also introduce additional dependencies of the star formation history large scale overdensity. These additional fluctuations might include a scale dependence that is different to that of cosmic variance, and could therefore introduce a scale dependent component of reionization induced galaxy bias.

For example, consider the epoch after HeIII overlap. At that time the mean-free-path for HeIII ionizing photons is limited by abundance and cross-section of Ly-limit systems, since the diffuse HeII has previously been ionized. During this epoch, heating of the IGM will be sourced by recombinations of HeIII ions. Now the recombination time is an order of magnitude longer than the Hubble time at the mean IGM density. However in the overdense regions con-

taining filaments and sheets the recombination time would be shorter, and could approach a Hubble time in high density regions. As a result, while regions of low overdensity would cool adiabatically by the cosmic expansion, heating due to photo-ionization of HeII could be substantial in the overdense regions. This effect would introduce temperature fluctuations inside overdense regions of the IGM on scales larger than the mean-free-path.

Thus, it is possible that the ionizing photon mean-free-path introduces a length scale below which reionization induced bias is independent of scale, but above which the reionization induced bias is scale dependent. At $z \sim 3$ the ionizing photon mean-free-path is ~ 100 comoving Mpc (e.g. Bolton & Haehnelt 2006). This scale is uncomfortably close to the scale of the baryonic acoustic peak, implying that careful account will need to be taken of reionization induced bias in galaxy surveys that select star forming galaxies. A proper analysis of this possibility would require full numerical modeling and is beyond the scope of the present paper.

8.3 Improvements to the model

In the future, our simple model could be improved in several ways. Our model predicts that galaxies in regions that are reionized earlier form a larger fraction of their stellar mass at later times, implying that these galaxies form a greater fraction of their stellar mass in more massive halos. We have assumed that the star formation efficiency is independent of halo mass. However if high redshift galaxies are subject to mass-dependent feedback effects (such as supernova feedback), then the star formation history would be altered. The presence of feedback in low mass halos would result in a larger fraction of the final stellar mass being formed after reionization, and hence in an increase in the sensitivity of the final mass-to-light ratio to the local reionization redshift. In addition, one could incorporate metal enrichment of the star formation. Stars forming in galaxies within overdense regions where reionization occurs early have their star formation, and hence their metal enrichment, delayed. As we have discussed, the resulting stellar populations are therefore observed to be younger at a low redshift z . Since there is a delay in the enrichment of the IGM following a burst of star formation, the younger stellar populations will have slightly lower metallicity. Thus the metallicity of populations observed at z should be slightly dependent on the reionization history. We expect that the lower metallicity in the younger populations would tend to reduce the magnitude of the reionization induced bias, since more highly enriched populations are bluer, and have lower mass-to-light ratios (though this would be a second order effect). On the other hand, since we have not included metal enrichment, our model also underestimates the variation between the UV fluxes of stellar populations with different ages, and hence also underestimates the contribution of reionization to the galaxy bias. In addition to metallicities, one might also attempt to include the effects of dust, which leads to larger extinction in younger galaxies (Shapley et al. 2001). This would redden the spectra of galaxies in regions that were reionized at earlier times.

9 CONCLUSIONS

We have developed a model to estimate the effect of reionization on the clustering properties of galaxy samples at intermediate redshifts. Current models of the reionization of the intergalactic medium predict that overdense regions will be reionized early due to the presence of galaxy bias. The IGM in these regions is heated through the absorption of the ionizing radiation. The heating leads to an increased Jeans mass, and so reionization suppresses the formation of low-mass galaxies. The suppression of low mass galaxy formation in turn delays the build up of stellar mass in the progenitors of massive low redshift galaxies. As a result of this delayed buildup, the stellar populations observed in galaxies at later times are on average slightly younger in overdense large-scale regions of the Universe. Stellar populations fade as they age and so the resulting age difference would lead to a lower mass-to-light ratio for galaxies in overdense regions. In volume limited surveys, such as those now being employed for large scale clustering studies, a fixed observed flux threshold therefore contains lower mass galaxies (on average) in overdense regions with a corresponding increase in the galaxy number density.

We have parameterized the reionization induced increase of the observed galaxy density in overdense regions in analogy with the traditional galaxy bias. Our modeling uses merger trees combined with a stellar synthesis code. We have used this model to demonstrate that reionization can have a significant and detectable effect on the clustering properties of galaxy samples that are selected based on their star-formation activity.

In existing samples of Ly-break galaxies, the bias correction for reionization is at the level of 10-20%, leading to correction factors between 1.5–2 in the mass inferred from clustering amplitudes. This effect is present in existing samples of Ly-break galaxies at $1 \lesssim z \lesssim 3$ (Steidel et al. 2003), and provides a systematic correction to existing analyses that is in excess of the statistical errors (Adelberger et al. 2005). For example the reionization induced bias qualitatively changes the conclusion of Adelberger et al. (2005) that Ly-break galaxies stop forming stars at $z \gtrsim 1$, and evolve into red elliptical galaxies by $z \sim 2$. Rather, allowing for reionization induced bias implies that Ly-break galaxies could evolve into the blue populations observed at low redshift with clustering lengths that are smaller than the massive red galaxy population.

The reionization of helium, and the associated additional heating of the IGM may lead to a sharp increase in the amplitude of the correlation function of $\sim 50\%$ for galaxies at fixed luminosity in the redshift range $3 \lesssim z \lesssim 4$. Our model predicts that the reionization introduced bias is approximately independent of scale. However we are unable to rule out scale dependence at the level of a few percent due to the limited numerical accuracy of our calculations. Further astrophysical complexities not addressed in our model could alter this conclusion. Future experiments aimed at measuring galaxy clustering at a precision level of a few percent over a large range of spatial scales (with a goal of constraining the initial conditions from inflation or the nature of dark matter and dark energy), will need to carefully account for this possibility.

We find that the contribution to the bias due to reion-

ization is fairly insensitive to halo mass. This is in contrast to the galaxy bias from enhanced structure formation in overdense regions which is a function of halo mass. Hence the fractional contribution to the galaxy bias by reionization is smaller for more massive systems, and as a result the systematic error introduced into the estimate of halo mass from clustering amplitude is less serious for more massive systems. We find that while the reionization bias is already effecting clustering studies of Ly-break galaxies, it will become even more important as future surveys begin to discover populations of less massive high redshift galaxies.

The reionization induced bias should be sensitive to the type of selected galaxies. In the case of Ly-break galaxies, we would therefore expect that the clustering amplitude would depend on the band in which the flux selection was performed. Alternatively, overdense regions would therefore be expected to have a slightly bluer population of galaxies. For Ly-break galaxies our model predicts the systematic offset in $U_n - G$ color to be $\sim 0.03 - 0.05$ magnitudes. Note that this offset refers to the correlation between color and large scale overdensity within a color-selected sample, and not to the galaxy population on average. The average galaxy population could show a different behavior. For example, galaxies in overdense regions are observed at low redshift to be redder because they formed earlier, or because their cold gas was heated by mergers or stripped by the hot IGM in clusters. A correlation between galaxy color and overdensity within a Ly-break galaxy sample would be evidence for the reionization induced galaxy bias, and could be used to calibrate its effect empirically.

Finally, we considered the importance of reionization induced bias for current and upcoming surveys attempting to detect baryonic acoustic oscillations. We find that the contribution to the bias from reionization is very small in surveys of old stellar population galaxies at $z < 1$, with corrections of $\lesssim 1\%$. We also find that reionization should not impact on measurement of the baryonic acoustic peak in samples of moderate redshift star-forming galaxies, due to the independence of the reionization induced bias on scale. However it is possible that the mean-free-path of ionizing photons introduces a length scale below which reionization induced bias is scale dependent, but above of which the reionization induced bias is scale dependent. The scale of the mean-free-path is uncomfortably close to the scale of the baryonic acoustic peak, implying that careful account will need to be taken of reionization induced bias in galaxy surveys that select star forming galaxies.

Acknowledgments We thank Dan Stark for helpful comments on an early draft of this paper. This work was supported by the Australian Research Council (JSBW) and Harvard University grants (AL). JSBW acknowledges the hospitality of the Institute of Astronomy at Cambridge University where part of this work was undertaken.

REFERENCES

- Adelberger, K. L., Steidel, C. C., Pettini, M., Shapley, A. E., Reddy, N. A., & Erb, D. K. 2005, *ApJ*, 619, 697
- Babich, D., & Loeb, A. 2006, *ApJ*, 640, 1
- Barkana, R., & Loeb, A. 2001, *Phys. Rep.*, 349, 125
- Barkana, R., & Loeb, A. 2004, *ApJ*, 609, 474

Blake, C., & Glazebrook, K. 2003, *ApJ*, 594, 665
 Bolton, J. S., Haehnelt, M. G., Viel, M., & Carswell, R. F. 2006, *MNRAS*, 366, 1378
 Bond, J.R., Cole, S., Efstathiou, G., & Kaiser, N. 1991, *ApJ*, 379, 440
 Budavári, T., et al. 2003, *ApJ*, 595, 59
 Coil, A. L., Newman, J. A., Kaiser, N., Davis, M., Ma, C.-P., Kocevski, D. D., & Koo, D. C. 2004, *ApJ*, 617, 765
 Bond, J. R., Cole, S., Efstathiou, G., & Kaiser, N. 1991, *ApJ*, 379, 440
 Davidsen, A. F., Kriss, G. A., & Zheng, W. 1996, *Nature*, 380, 47
 Dijkstra, M., Haiman, Z., Rees, M. J., & Weinberg, D. H., *Astrophys. J.*, 601, 666-675 (2004)
 Efstathiou, G., *Mon. Not. R. Astron. Soc.*, 256, 43-47 (1992)
 Eisenstein, D. J., et al. 2001, *AJ*, 122, 2267
 Eisenstein, D. J., et al. 2005, *ApJ*, 633, 560
 Fan, X., et al. 2006, *AJ*, 132, 117
 Glazebrook, K., et al. 2007, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0701876
 Heap, S. R., Williger, G. M., Smette, A., Hubeny, I., Sahu, M. S., Jenkins, E. B., Tripp, T. M., & Winkler, J. N. 2000, *ApJ*, 534, 69
 Hogan, C. J., Anderson, S. F., & Rugers, M. H. 1997, *AJ*, 113, 1495
 Jacobsen, P. et al. 1994, *Nature*, 370, 35
 Kaiser, N. 1987, *MNRAS*, 227, 1
 Kriss, G. A. et al. 2001, *Science*, 293, 1112
 Leitherer, C., et al. 1999, *ApJS*, 123, 3
 Mo, H. J., & White, S. D. M. 1996, *MNRAS*, 282, 347
 Press, W., Schechter, P., 1974, *ApJ*, 187, 425
 Pritchard, J. R., Furlanetto, S. R., & Kamionkowski, M. 2007, *MNRAS*, 374, 159
 Quinn, T., Katz, N., & Efstathiou, G., 278, L49-L54 (1996)
 Reimers, D. et al. 1997, *A & A*, 327, 890
 Reimers, D., Fechner, C., Kriss, G., Shull, M., Baade, R., Moos, W., Songaila, A., & Simcoe, R. 2006, *Astrophysics in the Far Ultraviolet: Five Years of Discovery with FUSE*, 348, 41
 Scannapieco, E., & Barkana, R. 2002, *ApJ*, 571, 585
 Schaye, J., Theuns, T., Rauch, M., Efstathiou, G., & Sargent, W. L. W. 2000, *MNRAS*, 318, 817
 Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Gialalisco, M., & Pettini, M. 2001, *ApJ*, 562, 95
 Sheth, R. K., Mo, H. J., & Tormen, G. 2001, *MNRAS*, 323, 1
 Sheth, R., Torman, G., 2002, *MNRAS*, 321, 61
 Sokasian, A., Abel, T., & Hernquist, L. 2003, *MNRAS*, 340, 473
 Spergel et al., 2006, *ArXiv Astrophysics e-prints*, arXiv:astro-ph/0603449
 Smette, A., Heap, S. R., Williger, G. M., Tripp, T. M., Jenkins, E. B., & Songaila, A. 2002, *ApJ*, 564, 542
 Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Gialalisco, M. 2003, *ApJ*, 592, 728
 Tegmark, M., et al. 2006, *Phys. Rev. D*, 74, 123507
 Theuns, T., Bernardi, M., Frieman, J., Hewett, P., Schaye, J., Sheth, R. K., & Subbarao, M. 2002, *ApJL*, 574, L111
 Theuns, T., Zaroubi, S., Kim, T.-S., Tzanavaris, P., & Carswell, R. F. 2002b, *MNRAS*, 332, 367
 Thoul, A. A., & Weinberg, D. H., *Astrophys. J.*, 465, 608-

116 (1996)
 Tytler, D. 1995, in *QSO Absorption Lines*, Proc. ESO Workshop G. Meylan ed., (Springer:Berlin), p. 289
 White, R., Becker, R., Fan, X., Strauss, M., 2003, *Astron J.*, 126, 1
 Volonteri, M., Haardt, F., & Madau, P. 2003, *ApJ*, 582, 559
 Weinmann, S.M., Maccio', A.V., Iliev, I.T., Mallema, G., Moore, B., 2007 arXiv:0705.0530
 Wyithe, J.S.B, Loeb, A., 2003, *ApJ*, 586, 693
 Wyithe, J. S. B., & Loeb, A. 2004, *Nature*, 432, 194
 Wyithe, J. S. B., & Loeb, A. 2007, *MNRAS*, 375, 1034

APPENDIX A: THE DEPENDENCE OF THE GROWTH FACTOR ON LARGE SCALE OVERDENSITY

In § 5 we used the fact that the details of the merger tree history are not sensitive to the local large-scale overdensity. In this Appendix we demonstrate this independence.

Consider the conditional probability function for the number of progenitors of mass between M' and $M' + dM'$ that a halo of mass M breaks into when one takes a small redshift step dz

$$\frac{dN}{dM'} = -\sqrt{\frac{2}{\pi}} \frac{M}{M'} (\sigma_{\text{cm}}^2(M') - \sigma_{\text{cm}}^2(M))^{-1.5} \times \frac{d\delta_{\text{crit}}}{dz} \left(\sigma_{\text{cm}}^2(M') \frac{d \log \sigma_{\text{cm}}}{dM}(M') \right) dz. \quad (\text{A1})$$

Equation (A1) is written in terms of comoving densities and variances (labeled with sub-script "cm"). This equation could be modified in the presence of a large scale overdensity, which we denote δ_{cm} when extrapolated to $z = 0$ (making it "comoving"), by adjusting the overdensity for collapse as is done to derive galaxy bias in the Press-Schechter formalism. This adjustment takes place in the term

$$\begin{aligned} \frac{d\delta_{\text{crit}}}{dz} &= \frac{\left(\delta_c \frac{D(\delta_{\text{cm}}, 0)}{D(\delta_{\text{cm}}, z+dz)} - \delta_{\text{cm}} \right) - \left(\delta_c \frac{D(\delta_{\text{cm}}, 0)}{D(\delta_{\text{cm}}, z)} - \delta_{\text{cm}} \right)}{dz} \\ &= \frac{\delta_c \frac{D(\delta_{\text{cm}}, 0)}{D(\delta_{\text{cm}}, z+dz)} - \delta_c \frac{D(\delta_{\text{cm}}, 0)}{D(\delta_{\text{cm}}, z)}}{dz}, \end{aligned} \quad (\text{A2})$$

where we have explicitly included both the dependence of the growth factor D on the comoving overdensity, and its normalization at $z = 0$.

There remains a possible dependence on large-scale overdensity in $d\delta_{\text{crit}}/dz$ through the dependence on the growth factor. However the variation of the evolution in the growth factor due to δ_{cm} is present both in the growth factor and in its normalization, so that the ratio $D(\delta_{\text{cm}}, 0)/D(\delta_{\text{cm}}, z)$ should be independent of δ_{cm} to leading order.

To demonstrate this we compute the case of a zero cosmological constant (as is appropriate at high redshift). Locally, we can model a region of large scale overdensity δ_{cm} as being carved out of a universe with a density parameter $\Omega_m(1+\delta_{\text{cm}})$, where Ω_m is the mean density parameter of our Universe. We can then compute the evolution of structure and the local relation between scale factor and time, within this modified universe. However when we observe galaxies in

the overdense region we see them at a redshift that is determined by the expansion history of the actual Universe, not of the overdense region. To compare the evolution of structure in the mean universe and overdense regions, we therefore need to consider the growth factor within the overdense region at a fixed time in the past (corresponding to the expansion of the actual universe), rather than at a fixed scale factor. Furthermore, the growth factor computed must then also be normalized by the growth factor in the overdense region at the current time in the usual way. We have

$$D \propto [\Omega_m(1 + \delta_{\text{cm}})]^{-1} a(\delta_{\text{cm}}). \quad (\text{A3})$$

Here $a(\delta_{\text{cm}})$ is the overdensity dependent scale factor, which is related to the age of the universe at $a(\delta_{\text{cm}})$ through

$$t = 2/3 H_0^{-1} [\Omega_m(1 + \delta_{\text{cm}})]^{-1/2} [a(\delta_{\text{cm}})]^{3/2}, \quad (\text{A4})$$

where H_0 is the local value of Hubble's constant. Substituting, we find

$$D \propto H_0^{2/3} (1 + \delta_{\text{cm}})^{-2/3} t^{2/3}, \quad (\text{A5})$$

and hence

$$D(t)/D(t_0) = (t/t_0)^{2/3}. \quad (\text{A6})$$

Thus the growth factor, normalized to the growth factor at the present day is independent of δ_{cm} (when the cosmological constant is ignored).

The above arguments imply that since δ_{cm} cancels in equation (A2), equation (A1), and therefore a merger tree is insensitive to the large scale overdensity. While structure forms earlier in overdense regions leading to an enhanced merger rate, there are more halos with which to merge so that the merger rate per halo remains constant.